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Abstract

The Fission Power Systems (FPS) project is developing a Technology Demonstration Unit (TDU) to verify the performance and functionality of a subscale version of the FPS reference concept in a relevant environment and to verify component and system models. As hardware is developed for the TDU, component and system models must be refined to include the details of specific component designs. This paper describes the development of a Sage-based pseudo-steady-state Stirling convertor model and its implementation into a system-level model of the TDU.

Introduction

The Fission Surface Power (FSP) project at the NASA Glenn Research Center (GRC) is developing technology to enable the option for fission power for planetary exploration. The FSP reference baseline concept consists of a 186-kW_t fission reactor, which provides heat to four 12-kW_e free-piston Stirling Power Conversion Units (PCUs). The waste heat from the convertors is then rejected through four cooling loops, each capable of radiating 35 kW_t through titanium-water heat pipes to radiator panels (5 per cooling loop). Current system-level models of the FSPS estimate that such a system could deliver 40 kW of reliable, round-the-clock electrical power with an estimated mass of 5820 kg (Fission Surface Power Team, 2010).

The FSP team is currently developing a Technology Demonstration Unit (TDU), which will consist of an electrically heated core simulator capable of producing up to 100-kW_t, a single 12-kW Stirling PCU, and a single 35-kW_t cooling loop. Thus, full-scale prototypes of components will be used in a quarter-scale system and operated in thermal vacuum. Since the TDU uses full-scale FSPS components operating in a relevant environment, verifying TDU system models is a key step in verifying FSPS system models. Prior to the completion of the design of the TDU components, system-level models of the TDU did not include detailed component models. However, as the TDU components are designed and fabricated, the detailed designs of these components can be included in detailed component models, which can be integrated into the system-level model. This will add fidelity to both TDU and FSPS system models.

Sage-Based PCU Model

Overview

System-level models of both the TDU and FSPS have modeled the PCU using either a Schmidt-cycle analysis or by simply assuming that the convertors would reach a fixed percentage of the Carnot efficiency at the design condition. While both of these techniques provide quick closed-form solutions and are useful for estimating performance near the design operating point, they are much less useful in predicting off-nominal performance required in transient and off-nominal steady-state simulations, and both are subject to somewhat subjective evaluations of convertor performance, which are not physics based.

In contrast, Sage models the physics of the actual convertor, coupling the solutions of heat transfer through the heat exchangers, gas volume pressure, and mass-spring-damper systems (Gedeon 2010). In addition, this model includes several parasitic losses commonly seen in actual convertors, including appendix gap losses, conduction losses, heat exchanger ineffectiveness, pressure drop, and alternator inefficiency. As a result, the Sage-based model, provided by Sunpower, gives the most accurate prediction currently available for convertor performance during both nominal and off-nominal operations. One disadvantage with using a Sage-based model is the loss of a closed-form solution. In addition, embedding a Sage model directly into a system-level model introduces an additional subsolver, which is called repeatedly by a top-level solver. This has been shown to dramatically increase computational time. To eliminate this requirement, the Sage model is run independently of the system model over the entire range of the intended operation, generating a comprehensive performance map, analogous to compressor or turbine maps used in Brayton cycle analysis. These performance maps can then be referenced by multi-dimensional interpolation functions in the system model, eliminating the need for nested solvers. The current performance map, which has more than 114,000 data points, was generated in approximately 1 week on a commercial laptop central processing unit (CPU). Since this performance map is design specific, any changes to the design of the PCU will require that a new performance map be generated.

Sage-Based Map Generation

The Sage model consists of a free displacer, a constrained piston, a rejector, a regenerator, and an acceptor, as well as expansion, compression, and buffer spaces. The rejector model contains a model of the water heat exchanger and therefore is defined by boundary conditions on the water mass flow and water temperature, both of which are inputs from the system-level solver during a given iteration. The cold-end heat exchanger on the PCU flows water circumferentially around the rejector. Since Sage can only resolve the axial dimension, it cannot apply the circumferential temperature gradient that is seen in the real convertor. To compensate for this, Sunpower uses a degradation factor that increases the cold-end temperature above the levels that would be predicted if this gradient were axial, providing a conservative estimate of convertor performance. The acceptor model does not contain a corresponding NaK heat exchanger model, so for the purpose of performance mapping, the boundary conditions that define the hot end are the metal temperatures at the inlet and outlet of the acceptor. The system level model then incorporates a NaK heat exchanger and iterates to determine the correct relationship between NaK inlet temperature, NaK flow rate, NaK outlet temperature, and heat input to the convertor.

The performance maps were generated using the commercial mathematics programming environment MATLAB to call Sage within a nested loop structure throughout the entire range of intended operation. Inputs to the map include hot-end temperature, hot-end axial temperature difference, water temperature, water mass flow rate, and amplitude. The outputs are net heat input, electrical output, heat rejected, and thermal efficiency. The hot-end temperature ranged from 250 to 950 K in 25 K increments, hot-end temperature difference from 0 to 150 K in 15 K increments, water temperature from 250 to 450 K in 25 K increments, water mass flow from 0.01875 to 0.5875 kg/s in increments of .05 kg/s, and piston amplitude ranged from 8 to 20 mm in increments of 2 mm, resulting in approximately 114,000 performance map points covering a five dimensional parametric space. In addition to this, better resolution was obtained in specific areas of interest. It should be noted that each PCU consists of two Stirling generators in a symmetric, thermodynamically coupled, dual-opposed configuration. Therefore the Sage analysis is performed on one-half of the convertor, and the results are applied to both convertors in the system model.

Results

The charts below are a selection of data points taken from the performance maps. Figure 1 shows power output plotted against piston amplitude at various hot-end temperatures for one Stirling generator (one-half the full PCU). The trend appears to become increasingly linear as the convertor approaches its design operating temperature, with some curvature introduced at low hot-end temperatures. This trend is consistent with measured values taken during prior testing on kilowatt-class Stirling convertors (Briggs, 2010). Figure 2 shows efficiency plotted against piston amplitude at the same operating conditions. The peak efficiency appears to occur at piston amplitudes well below the nominal amplitude of 16 mm. This is not entirely unexpected, as the PCU was not designed for optimum efficiency due, in part, to system-level trades that allow the radiator mass to decrease as the cooling water temperature, which can be accomplished by increasing the amount of waste heat rejected by the convertors.

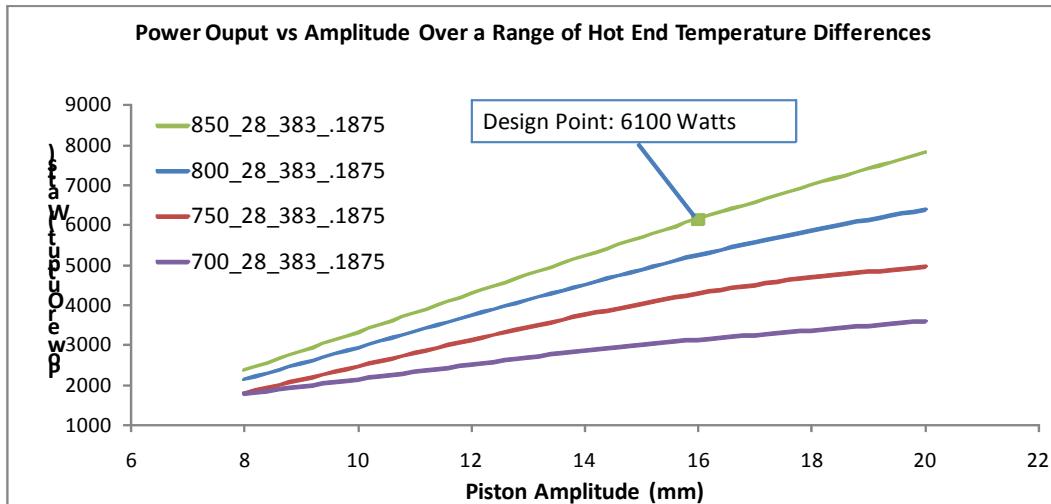


Figure 1.—Power output vs. piston amplitude at various hot-end temperatures for one Stirling generator (half of the PCU) operating with a 28 K hot-end temperature drop, a 383 K inlet water temperature, and a 0.1875 kg/s mass flow rate.

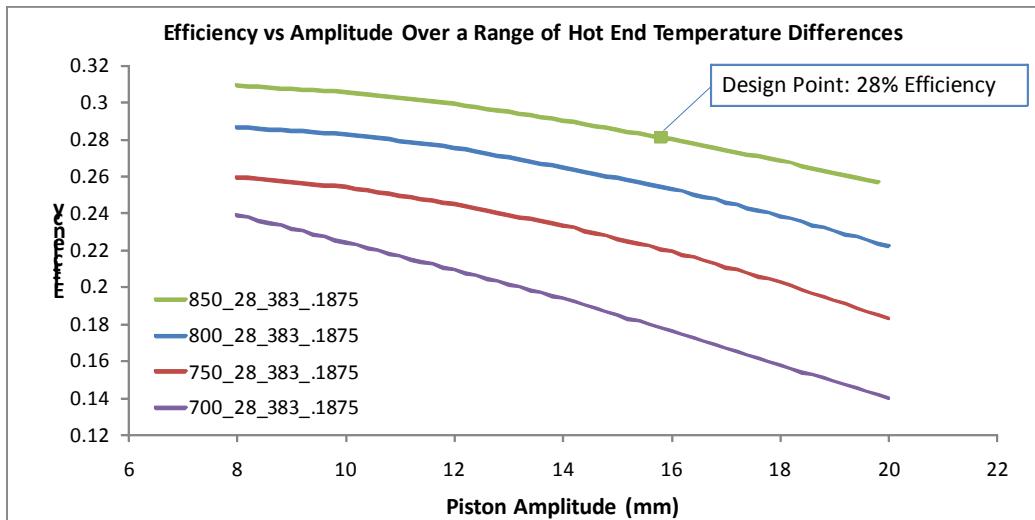


Figure 2.—Efficiency vs. piston amplitude at various hot-end temperatures for a convertor operating with a 28 K hot-end temperature drop, a 383 K inlet water temperature, and a 0.1875 kg/s mass flow rate.

Figure 3 shows the power output of one Stirling convertor plotted against the hot-end temperature difference at various piston amplitudes for one Stirling generator operating at a 850 K hot-end temperature, a 383 K inlet water temperature, and a 0.1875 kg/s mass flow rate. This plot shows that the power output is more sensitive to hot-end temperature difference at high amplitudes. This indicates that especially, at high amplitudes, it is important to provide sufficient NaK mass flow to the convertor. As discussed previously, determination of the appropriate relationship between hot-end temperature difference, net heat input to the convertor, and NaK mass flow rate will be left to a system-level solver, which will incorporate a component model of the NaK heat exchanger. Figure 4 shows the efficiency plotted against a hot-end temperature drop for the same set of operating conditions. Again, we see that the convertor attains higher efficiencies at lower piston amplitudes, and that increasing the temperature drop across the hot end results in a reduction in the efficiency of the convertor.

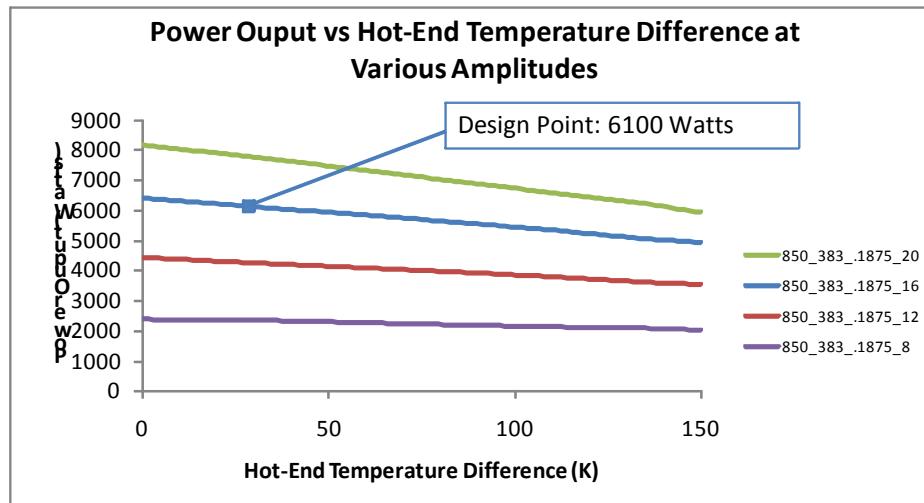


Figure 3.—Power output vs. piston amplitude at various amplitudes for one Stirling generator (half of the PCU) operating at 850 K hot-end temperature, a 383 K inlet water temperature, and a 0.1875 kg/s mass flow rate.

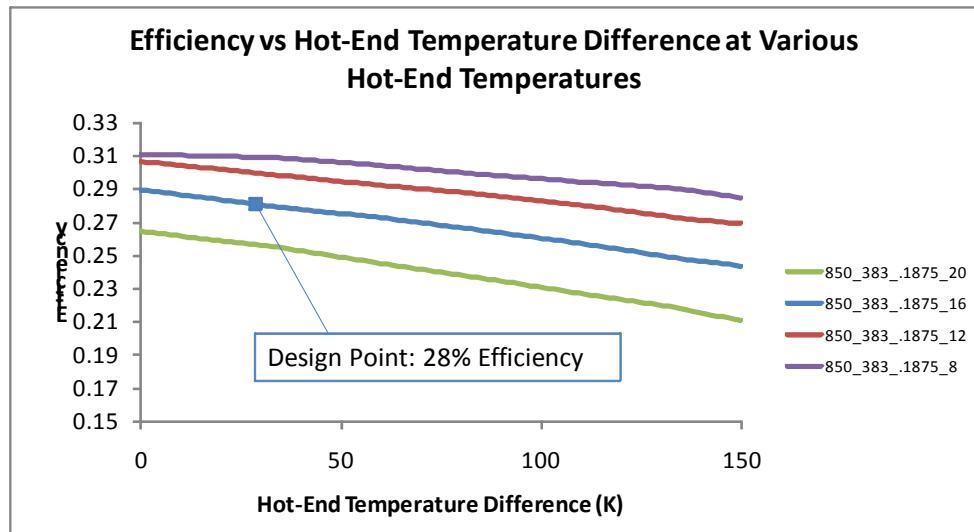


Figure 4.—Efficiency vs. piston amplitude at various amplitudes for a convertor operating at a 850 K hot-end temperature, a 383 K inlet water temperature, and a 0.1875 kg/s mass flow rate.

Conclusion

System-level models of the Fission Power System (FPS) Technology Demonstration Unit (TDU) are being updated with detailed component-level codes as hardware designs are completed and fabrication begins. These updated models will be used to improve the accuracy of steady-state performance and transient response predictions for the TDU system, beyond what was previously available using simplified modeling techniques. Verification of detailed system-level TDU models with test data will allow for improvements to be made in system-level models of the FSPS, which can be used to verify performance claims as well as transient response analyses. A detailed performance map of the PCU has been generated using a Sage model provided by Sunpower, the designer of the PCU hardware. This performance map is currently being integrated into a system level model, allowing for improved accuracy while maintaining sufficient computational speed.

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